ISSN 2079-0961, Arid Ecosystems, 2011, Vol. 1, No. 1, pp. 53–58. © Pleiades Publishing, Ltd., 2011.

APPLIED PROBLEMS
OF ARID LANDS DEVELOPMENT

Soil Pollution with Heavy Metals in Mine Environments, Impact Areas of Mine Dumps Particularly of Gold- and Copper Mining Industries in Southern Africa[1]

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Received May 04, 2010

Abstract—Waste products of the mining industry are very important factors in the field of environmental pollution, soil pollution particularly. In the following case studies soil pollution with heavy metals in the surroundings of tailings dumps from gold- and copper mining industries, was investigated. In order to enhance knowledge about mine dumps and to provide relevant institutions in the region with identification methods, a GIS approach has been developed. The results of the studies made it possible to identify such surface soils of tailings dumps as had been severely polluted by heavy metals. This is demonstrated in two study areas in the SADC region.

Keywords: soil pollution, gold mining, copper mining, South Africa, Zambia, tailings dumps, heavy metals.
DOI: 10.1134/S2079096111010082

INTRODUCTION

Wide areas of the SADC Region are affected by environmental pollution detrimental to industrial and agruicultural use as well as to the quality of nature and landscape. The sources of contamination are industrial facilities and waste sites as well as traffic, dumps and a diversity of other sources of hazardous substances. Chemicals used in agruiculture contributed heavily to soil pollution. The highest environmental risks are caused by toxic metals, polycyclic aromatic hydrocarbones, pesticides and nitrates.

Along with the development of the economies in the SADC countries, there is an increase in demands for environmental protection, especially in the mining areas. There appears to be growing confrontation among citizen groups, governmental agencies and members of the mining industry. The degree of conflict and its nature usually depends on the current land use and the estimated consequences of proposed disturbances. The conflict has centred in following issues: destruction of landscapes, degradation of the visual environment, disturbance of watercourses, destruction of agruicultural and forest lands, damage of recreational lands, noise pollution, truck traffic, sedimentation an erosion, land subsidence, vibration from blasting and air blasts, air pollution, soil pollution etc.

These impact processes require a proper study in order to appreciate the extent of environmental degradation. Using GIS as a tool in this study, it is possible to create a complete survey of mine dumps in the study areas.

In order to enhance knowledge about mine dumps and to develop and provide methods for the relevant institutions in the region, two case study areas were identified:

Copperbelt Area—Zambia—copper mining;

Carletonville Area—South Africa—gold mining.

PROBLEMS ASSOCIATED WITH GOLD MINING IN SOUTH AFRICA—A CASE STUDY IN THE WONDERFONTEIN BASIN (FAR WEST RAND)

Gold mining activities in South Africa are mainly concentrated in an area known as the Golden Crescent. It is an area stretching from the south east of Johannesburg in the vicinity of Springs, through that city further west and south west over a distance of approximately 400 kilometres to the south of Welkom.

The gold is contained within the conglomerates of the Witwatersrand Supergroup and the deposits can be dated at approximately 2800000 to 2300000 years BP (Kent, 1980). The gold bearing reefs also contain minerals such as pyrite, traces of silver and other metals including variable amounts of uranium.

This investigation will concentrate on a portion of an area known as the West Rand Goldfields. These Goldfields are situated to the west and southwest of Johannesburg and east northeast of Carletonville.

[1] The article is published in the original.

The upper Mooi River drains the present day area, particularly by the so-called Wonderfontein and Loopspruit tributaries. In the study, only problems associated with mines in the Wonderfontein tributary will be discussed.

The gold ore is crushed and the gold and other minerals in the ore are extracted through flotation processes. The resultant slimes are then deposited in built up slime dams. The quality of extraction has improved through the years. In some of the older slime dams the amount of gold still present in the slime is enough to enable the mines to rework the slimes for the recovery of the gold still present. Most of the mines in the area are fairly deep and gold is mined at depths ranging from approximately 1 to 4 km.

Various environmental problems are caused by the mining industry in the study area. The more important problems are associated with the dumping of waste in the form of massive rock dumps and Slime dams (tailings). Not only are these dumps aesthetically unpleasing but they are also responsible for pollution plumes. Slime dams occupy an area of approximately 25 square kilometers in the Wonderfontein study area.

In order for Sidewalls of the dams to be as dry as possible, it was decided by some of the mining companies to locate the slime dams on the dolomite. This results in a fairly large amount of seepage into the underground aquifer. Not only the original moisture in the slimes, but also infiltrated rainwater can eventually land in the underground water. It is difficult to quantify the amount of water that eventually lands in the underground aquifer. Some of the slime dams were even constructed over existing sinkholes. In order to try and stabilize these dams, large amounts of slimes are pumped into existing sinkholes.

The next environmental problem caused by the mining activities in the study area is related to the radioactive issue (Radioactive Monitoring Report, 1997). As has been mentioned in the introductionary paragraph, a significant amount of uranium is present in the ore being mined. H. Coetzee et al. (1997) had used surface radioactivity to trace radioactive precipitates in the vicinity of mining activities. Data from the Radioactive Monitoring Committee (1997) confirms that there is radioactivity present in samples obtained from localities in the study area. In 2006 a report from Coetzee H., Wind F. and Wade P.W. confirms the high risk of radioactive water pollution in the Wonderfonteinspruit Catchment.

METHODOLGY AND ANALYSES—CASE STUDY SOUTH AFRICA

For the purpose of the case study soil samples were collected to identify the impact from Tailings—Dump—Carletonville—Doornfontein Mine Dump on surface soil pollution at several distances from the dump. Samples were taken from the soil surface of ca 0.25 qm at depth of 0–5 cm. To make sure that the results are comparable, all samples were taken under grassland.

Vegetation parts were removed, and samples were dried and sieved. The applied analytical technique used to determine the total concentration of specific elements in such samples was atomic absorption spectrometry. The analytical results are summarized in Table 1. The measured ph (KCL) in the samples showed that the tailings material was highly acidic, with levels between 4.5 and 5.5, the acidity increased slightly with increasing distances from the edge of the dump, as follows: to 4.1 at 500 m distance, and 4.5 at 2000 m distance.

An interesting finding was, that at the edge of the dump, the concentration of heavy metals like Cr, Co, Ni, As, Pb, Cu, Hg, U and Zn is almost lowest, and highest at 100 to 200 m Distance from the edge of the dump. The minimum level of heavy metals was measured in the dump material itself and often at the edge of the dump.

Two possible reasons are assumed. Firstly, it may be the wash out effect of the suspended solids with wind and water erosion. Since the slope of the dump is not revegetated, these processes are supported by the special climatic conditions of the tropical climate.

Secondly: the very high acidity of this soil samples increases the mobilization of heavy metals in soils (Table 2). Toxic heavy metals like As and Hg are washed out into ground and surface water starting from pH 4.5. This is a major risk for human health in the region.

PROBLEMS ASSOCIATED WITH COPPER MINING IN ZAMBIA—A CASE STUDY IN THE ZAMBIAN COPPERBELT

Mining and smelting in Zambia dates back to A.D. 650 when operations were on a village scale and were replaced by large scale operations in the first half of the 20th century. In 1928, Anglo–American Corporation initiated high level exploration and this was sustained until 1940 when concessions ended. By 1969 a combined production of 720000 tons metal copper from discovered deposits was achieved in the Copperbelt (EMP, 1996).

The area of interest encompasses the Nkana Central, Nkana South Orebody (SOB), Mindola, Chambishi and Chibuluma mines. These mines are located in and around Kitwe, the third largest city, situated some 400 km north of Lusaka, the capital of Zambia. Kitwe and its satellite towns of Kalulushi and Chambishi have a combined population of 490000 people.

The mines are situated on the north-eastern and south western sides of the Chambishi-Nkana Basin, which lies to the west of Kafue Anticline. The basin is traversed and drained by streams such as Mwambashi, Kitwe, Mindola, Uchi, Wusakile, Luanshimba, Kamuchanga, Mululu, Kalulushi, Kankashi and Chibuluma, which eventu-

Table 1. Surface soil pollution (in ppm) by Doornfontein Mine Dump, Carletonville

No Direction, distance in m	Co	As	Se	Au	Hg	Pb	U	pH (KCl)
1-SE edge	16	13	25	0	0	9.1	6.3	2.7
2-SE58	39	5	13	0.1	0	19.7	8.2	4.2
3-SE83	37	7	26	0.1	0	20.8	4.4	4.1
4-SE110	46	10	26	0.2	3.7	24.4	4.0	4.1
5 SE200	43	7	18	0.1	0	19.5	4.7	4.0
6-SE350	31	9	23	0.3	0	31.3	3.3	4.1
7-SE400	33	7	22	0	0	11.9	2.1	4.1
8-SE500	25	5	11	0.1	0	8.5	1.9	4.1
1-Nedge	4	23	0	0	22.9	8.9	2.3	3.6
2-N50	39	9	8	0.2	0	16.2	4.7	4.1
3-N100	41	11	20	0	0	16.3	3.7	4.3
4-N200	38	39	22	0.5	0	23.1	15.9	3.9
4a-N200	19	42	9	0.4	0	18.3	18.9	3.9
5-N300	44	23	0	0.4	0	26.0	15.4	4.0
6-N400	44	14	3	0.7	0	12.9	6.6	4.4
7-N-500	46	26	0	0.3	0	18.5	21.9	4.1
8-N-edge	51	208	35	0.6	0	55.8	57.2	2.8
9-N1000	54	6	1	0.3	1.2	13.4	31.1	6.4
P3 60-60 cm	178	8	0	0.4	0	78.5	3.3	4.3
P2 10-30 cm	81	10	32	0.8	4.4	31.7	5.2	4.1
P1 0-10 cm	12	30	19	0	1.1	9.9	12.3	3.3
10-N1500	40	10	31	1.0	0	10.0	10.9	7.1
11-N2000	33	3	3	0	0	20.1	2.0	4.5

Table 2. Values of pH for a starting Mobilisation of heavy metals in soils (Blume, 1992)

Cd	Zn	Ni	Co	Al	Cu	As	Cr	Pb	Hg
6.5	6.0–5.5	5.5	5.5	5.5	4.5	4.5–4.0	4.5–4.0	4.0	4.0

ally flow into the Kafue River. This is not only the most impostant river as it supports about 40% of the 9 million People, but also the most polluted one in Zambia, mainly due to mining activities in the Zambian Copperbelt in the Upper Kafue and industrial and agruicultural activities in the Mazabuka and Kafue towns in the Lower Kafue.

The Nkana Mining Area is some 11217 hectares in extent and it is located west of Kitwe, which is situated approximately in the centre of the Zambian Copperbelt. The Nkana Mining Area comprises mainly the South Orebody (SOB), Nkana Central and Mindola Underground Mines.

Metallurgical processing of ores for copper/cobalt extraction has produced, over a period of over 30 years of mining, tailings dams covering a significant surface area. Tailings dumps, most of which are not operational, exist in the Nkana Division area covering a total surface area of 1579.9 ha and contain a total of 224.82 million tones of sulphide ore waste.

Table 3. Surface soil pollution of heavy metals (in ppm) of a tailings dump Kitwe (Zambia)

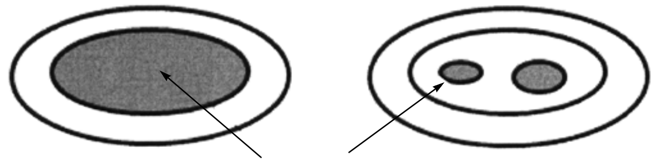
Direction and distance in m	Pb	Cu	As	Ni	Zn	Co	pH (KCL)
TD 52	6	3380	13	19	26	405	8.3
N	77	14436	22	29	152	983	6.8
N50	50	9372	60	42	269	1722	7.5
N100	87	21433	24	25	105	454	5.7
W	20	3255	15	21	55	530	7.4
W50	60	13392	26	32	119	797	6.6
W100	45	10294	16	22	80	519	6.7
S	12	3094	9	19	38	332	7.4
S50	45	9245	17	27	134	664	6.7
S100	32	9045	11	22	66	389	6.4
TD60	0	3437	3	14	4	147	7.2
S	16	3185	4	20	41	316	6.9
S50	–	–	–	–	–	–	5.2
S100	44	7339	13	61	84	286	4.0
W50	9	1332	5	54	29	74	5.3
W100	434	11833	20	50	1312	631	4.2
N	6	1627	4	63	24	333	6.3
N50	7	1402	5	83	20	122	5.1
N100	13	1935	5	92	30	115	4.9
Reference soil	10	885	3	16	16	33	4.2

METHODOLGY AND ANALYSES—CASE STUDY ZAMBIA

Surface soil samples were collected to identify the impact of pollution by tailings dumps 52 and 60 on surface soil at several distances from the dumps (The Soils of the Copperbelt Province, 1992). Samples were taken from the soil surface of about 0.25 qm at depth 0–0.5 cm. To make sure that the results were comparable, all samples were taken under grassland.

Vegetation parts were removed, and samples dried and sieved. The applied analytical technique used to determine the total concentration of specific elements in such samples was atomic absorption spectrometry. The analytical results are summarized in Table 3. The measured ph (KCL) in the samples showed that the tailings material was alkaline with pH 7.2–8.3. Since the pH of the neutral soils in the area was quite acidic, with levels between 4.1 and 5.5 (Chirwa, Sichinga, 1996) the acidity was higher with increasing distances from the edge of the dump.

An interesting finding is that in our case the concentration of copper heavy metals like Cu, Co, Ni, As, Pb and Zn is almost highest in 100 m distance from the edge of the dump. The minimum level of heavy metals was measured in the dump material itself and often at the edge of the dump. A possible reason may be the washout effect of the suspended solids with wind and water erosion. Since the slope of the dump is not revegetated, these processes are supported by the special climatic conditions of the tropical climate. Since in the Copperbelt these dumps are often situated in the flood plains of the river basin, there are high inputs of suspended solids like toxic heavy metals into the streams. The increase in siltation processes is a known fact of environmental degradation due to water erosion of mine dumps since there are sensitive landuses such as townships, in the impact area—the effect on human health should be considered in further investigations.



Overview of phases to inventories environmental impact zones of mine dumps.

DESCRIPTION OF A GIS APPROACH—MAPPING THE POLLUTION LEVEL IN THE VICINITY OF TAILINGS DUMPS IN THE SELECTED MINING AREA

The main aim of the case studies is to develop modules in environmental analysis of tailings dumps, methods of identification and evaluation of environmental impacts of dumps within a GIS-based environmental management system. In this regard, the experience with the KatBo System (Zierdt, 1996), which was developed and used for monitoring and studying environmental problems related to copper mining activities of the Mansfeld Region in East Germany, has been integrated in the project. (Weissenstein et al., 2000).

HOW ARE MINE DUMP INTEGRATED IN THE GIS—SYSTEM?

Several steps to inventories impact zones of mine dumps are shown in figure, Table 4. As usual data collection is necessary, at first one need to define the input criteria - there can be anthropogenic and natural criteria. To specify the type and size of the tailings dump – it is important to analyse topographical maps, aerophotos or to do field mapping. Natural input criteria are information about type of relief, main wind direction, vegetation and soil. These main factors influence the distribution of pollution in soils. Two types of migration of pollution can be distinguished—pollution areas of large dumps and areas of dumps from small scale mining. The last ones are often situated in agricultural areas and have short distances between themselves. There often is a high content of ore in the surrounds of the dump. The areas of these dumps will be mapped as small mine dump fields with a maximum impact area from the edge up to 250 m.

The material of larger dumps (tailings) is very fine und is migrating with wind and water erosion. The main pollution impact of these dumps can be predicted at 500 m from the edge of the dump. For further risk assessment analysis a reference concentration of

Table 4. Manual for implementation in a GIS

Input Criteria	Anthropogenic Criteria	Natural Criteria
Type and size of Mine Dumps	Type of Mine Dumps Large Dumps (more than 1 ha) Dumps from Small Scale Mining	Relief Vegetation Soil Type
Data Source	Data Collection Topographical Maps, aerophotos Field Mapping Environmental Agency	Data Collection
Migration of Pollution	*Large Dumps* Wind Erosion Pollution with heavy metals	*Dumps from Small Scale Mining* High contents of ore in the surrounds of the dump Often situated in agruicultural areas Short distances between different dumps
Identification of the Impact Area from the edge of the Dump	The pollution impact from large dumps can be predicted at 500 m from the edge of the dump	The areas of this dumps will be mapped as small mine dump fields with a maximum impact area from the edge up to 250 m
Manual for implementation in a GIS	See figure below	
Risk Assessment	For example: Reference concentration of heavy metals (Cu) in soils in the Kitwe Study Area—Zambia: 0–10 m 15000 ppm 10–100 m 10000 ppm 100–500 m 1000 ppm	

heavy metals in soils should be measured in 1500–2000 m from the edge of the dump. For implementation of zones of impact of dumps into a GIS typical dumps should be selected and soil pollution further investigated. These results should be applied on similar dumps in the study area.

CONCLUSIONS AND OUTLOOK

The present results represent part of the study as has been carried out only. For the purpose of evaluating any impacts of tailings in terms of heavy metal pollution of surface soils, different zones of pollution around the sources have been distinguished—such as can be used in similar areas elsewhere, as a without-sampling-method in order to map the pollution level in the vicinity of tailings. The material of larger tailings dumps is very fine und is subject to migration with wind and water. The main impact of these dumps in terms of surface soil pollution can be predicted at 500 m from the edge of a dump. For further risk assessment analysis a reference concentration of heavy metals in soils should be measured at 1500–2000 m from the edge of the dump. For the implementation of zones of impact of dumps into a GIS, typical dumps should be selected and soil pollution further investigated. This method can be used for mapping and for tracing back soil pollution trajectories to their original sources.

It is clear from the above discussion that there are indeed several environmental problems in the study areas due to mining activities (past and present). When comparing the studied area to the total area where gold mining occurs in South Africa and the whole of the Copperbelt of Zambia, one realizes that the extent of the problems is potentially larger still. Solutions to these problems can only be achieved through concerted research efforts.

During the last 10 years a lot of research work has been carried out in both study areas—in the South African case study area particularly, data have been integrated in a GIS and an EMS. The experience of national as well as international agencies concerned with environmental problems as described is indeed of prime importance.

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